

Northumbria Research Link

Citation: Le Minh, Hoa, Ghassemlooy, Zabih, O'Brien, Dominic and Faulkner, Grahame (2010) Indoor gigabit optical wireless communications: challenges and possibilities. In: The 12th International Conference on Transparent Optical Networks (ICTON), 27 June- 1 July 2010, Bavarian Academy of Sciences and Humanities, Munich, Germany.

URL: <http://dx.doi.org/10.1109/ICTON.2010.5549136>
<<http://dx.doi.org/10.1109/ICTON.2010.5549136>>

This version was downloaded from Northumbria Research Link:
<http://nrl.northumbria.ac.uk/id/eprint/1798/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)



**Northumbria
University**
NEWCASTLE



UniversityLibrary

Indoor Gigabit Optical Wireless Communications: Challenges and Possibilities

Hoa Le Minh*, Zabih Ghassemlooy*
Dominic O'Brien**, Grahame Faulkner**

* School of Computing, Engineering and Information Sciences, Northumbria University
Newcastle Upon Tyne NE1 8ST, United Kingdom

** Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, United Kingdom

Email: {hoa.le-minh,z.ghassemlooy}@northumbria.ac.uk, {dominic.obrien,grahame.faulkner}@eng.ox.ac.uk

ABSTRACT

Indoor Gigabit optical wireless communication systems have the potential to offer multiple high-speed data services that can be delivered to homes via an optical fibre cable in the near future. In this paper we will discuss the challenges involved in the design of such systems and future possible advances. Results from a recent cellular Gigabit prototype link will also be presented and discussed.

Keywords: Optical Wireless Communications, Visible Light Communications, Infra-Red Communications, Light Emitting Diode.

1. INTRODUCTION

Full use of the capacity provided by the fibre delivered to homes will necessitate the use of broad-band links including indoor wireless access technologies capable of operating at Gbit/s. In recent years optical wireless (OW) has emerged as a strong candidate for high speed indoor communications [1-3], as a complementary scheme to RF systems. The main advantages of optical wireless communications are unregulated and unlicensed electromagnetic spectrum, high quality data transmission, immunity to electromagnetic interference and highly secured communications.

Indoor OW communications includes two main technologies: visible light and infra-red communications (IRC). Concerns about energy saving in general lighting are leading to the replacement of incandescent and fluorescent lamps with more energy-efficient solid-state lighting (SSL) devices. These SSL visible light sources can provide communications as well lighting, and this emerging technology has recently drawn great interest in research and practical applications [4-6]. IRC technology is relatively well developed and there are various applications and devices which conform to the Infrared Data Association (IrDA) standards [7]. In recent years we have seen a growing interest in applications of IRC for high speed indoor communications including broadband data services delivered to home and offices [5].

In this paper we will summarise current technologies that enable Gbit/s visible light and infra-red communications. Section 2 presents strategies to achieve a Gbit/s visible light communication link. In Section 3 results from a Gbit/s cellular IRC system are summarised. Challenges in design and implementation of VLC and IRC systems at Gbit/s data rates are discussed in Section 4.

2. VISIBLE LIGHT COMMUNICATIONS

2.1 White LED Source

White LEDs used for general illumination are of two types: (i) devices that combine separate red-green-blue (RGB) emitters and (ii) devices that use a blue emitter in combination with a yellowish phosphor. The latter is the preferred option for lighting because of lower complexity compared to the three-emitter device. The typical modulation bandwidth of these devices, however, is a few MHz [8, 9]. This bandwidth limitation is mainly due to the slow temporal response of the phosphor. A typical VLC link utilising a white LED is shown in Figure 1(a), where lighting and the communication link are both provided by the LED. The blue light can be readily extracted from the incoming optical beam by using an optical filter at the receiver and this increases the bandwidth substantially.

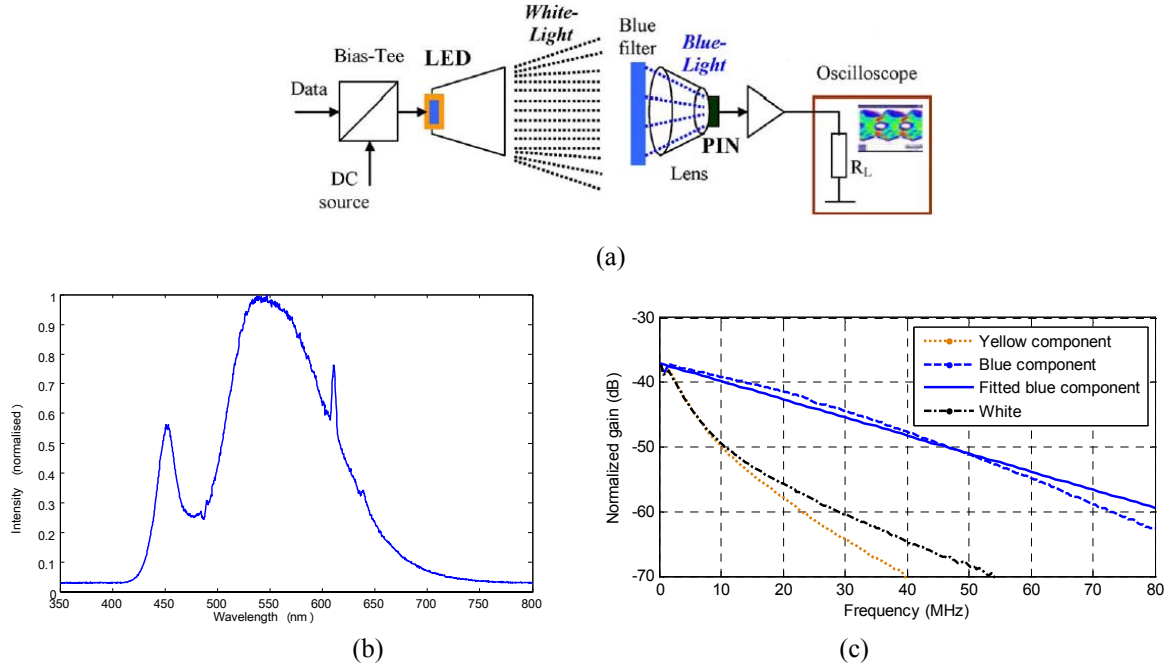


Figure 1: (a) VLC link; (b) LED optical spectrum of Luxeon Star white-light LED; (c) modulation bandwidths of white/yellow/blue components and blue-response fitting curve.

Figure 1(b) and (c) show the optical spectrum of emitted white light and the measured modulation bandwidth of the blue-phosphor LED, respectively. It is observed that the bandwidth of the white component of LED (~ 2 MHz) is much smaller than bandwidth of the blue component ($\sim 15 - 20$ MHz, depending on the LED type) [9, 10].

2.2 High-Speed VLC Links

Transmitting high data rates over a narrow modulation bandwidth is very challenging. There are a number of approaches to improve the modulation bandwidth, including using a blue-filter at the receiver to filter out the slow-response yellowish components, pre-equalisation at the LED driving module [8], post-equalisation at the receiver [10] or a combination of these techniques. Another approach to achieve high-speed data transmission over a limited bandwidth is to employ more complex modulation schemes where multiple bits can be carried by each transmitted symbol. In [11] a high data transmission rate, up to 231 Mbit/s, over a blue channel bandwidth has been reported. This approach utilises Discrete Multi-tone Modulation (DMT) in combination with the Quadrature Amplitude Modulation (QAM) scheme. Table 1 gives a summary of reported data rates for different VLC systems for white and blue channels as well as non-return to zero (NRZ) on and off keying (OOK) and DMT-QAM modulation schemes.

Table 1. Performance of high speed VLC systems.

	Pre-equalisation	Post-equalisation	Modulation scheme	Modulation bandwidth	Demonstrated data rate
White channel			OOK-NRZ	2 MHz	10 Mbit/s ($\text{BER} < 10^{-6}$)
White channel	x		OOK-NRZ	25 MHz	40 Mbit/s ($\text{BER} < 10^{-6}$) [8]
Blue channel	x		OOK-NRZ	45 MHz	80 Mbit/s ($\text{BER} < 10^{-6}$) [12]
Blue channel		x	OOK-NRZ	50 MHz	100 Mbit/s ($\text{BER} < 10^{-9}$) [10]
Blue channel			DMT-QAM	25 MHz	100 Mbit/s ($\text{BER} < 10^{-6}$) [9]
Blue channel			DMT-QAM	50 MHz	231 Mbit/s ($\text{BER} < 10^{-3}$) [11]

These results show that higher data rates are achievable utilising a blue channel in combination with pre/post equalisation or complex modulation schemes. Transmission of OOK-NRZ over an equalised channel is simpler compared to the complex modulation schemes since the latter require a large amount of signal processing at both transmitting and receiving ends. In both cases the ratio of the achievable transmission data rate over the raw LED modulation bandwidth (~ 2 MHz) is significantly enhanced. However, to achieve a wide modulation bandwidth using equalisation or employing multi-level modulation schemes the system will require a very high signal-to-noise ratio as outlined in [10, 11]. Therefore it is extremely challenging to achieve Gbit/s transmission rates using a VLC link.

2.3 Multiple-Input-Multiple-Output (MIMO)

In MIMO systems multiple transmitters (LEDs) and receivers (photo-detectors) are used to improve communication performance [13, 14]. The use of MIMO techniques offers the potential for increased link range and higher data throughput without the need for additional power or bandwidth, by the way of higher spectral efficiency (more bits/s/Hz), link reliability and/or diversity. Thus, it is of prime importance in wireless communications. Figure 2(a) shows a typical VLC MIMO system. Four LED arrays are used for room lighting as well as for transmitting four independent data stream simultaneously. A receiver array is composed of four photo-detector elements with non-imaging concentrators [13].

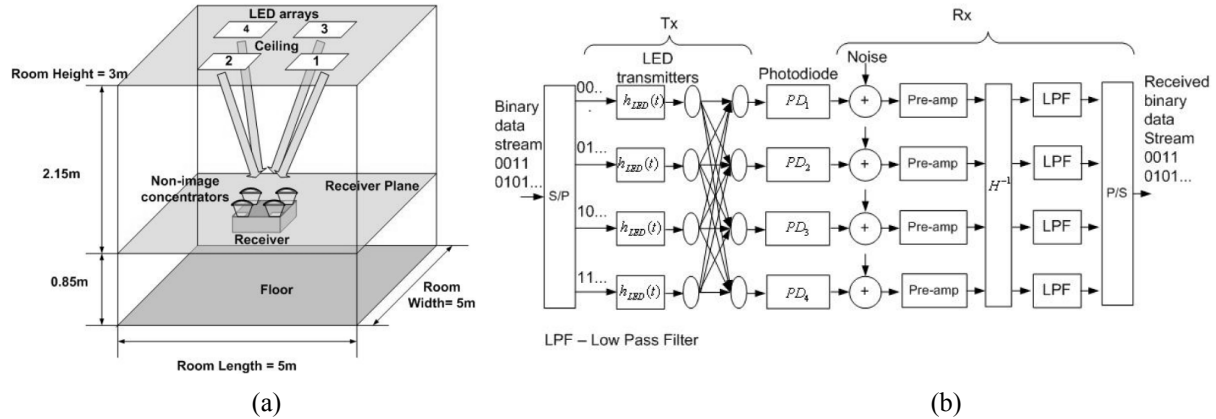


Figure 2: (a) VLC MIMO system; (b) Schematic of VLC MIMO model.

Figure 2(b) depicts the schematic of the MIMO model. Serial input data stream is interleaved and used to modulate the individual LED arrays (transmitters). Light emitted from each of the LED arrays is collected by all receivers, but with different strengths due to the geometric configuration. Received signals from all four channels are processed using a channel matrix H to recover the transmitted data streams corresponding to individual channels. Results obtained from [13] show that it is potentially possible to transmit NRZ-OOK data at rates exceeding 1 Gbit/s in many situations. In Table 2, the simulation data illustrates that using 36 channels will enable Gbit/s transmission. The system parameters and the details of simulation setup are reported in [13].

Table 2. Simulation results of VLC MIMO system

	White channel			White channel + equalisation			Blue channel		
Number of channels	4	16	36	4	16	36	4	16	36
Data rate (Mbit/s)	48	192	432	120	480	1080	160	640	1440
Lens diameter (cm)	0.2	0.44	0.71	0.44	0.8	1.38	1.6	3.6	7.14
Detector size (cm)	0.74×0.74	1.68×1.68	3.05×3.05	1.65×1.65	3.08×3.08	5.91×5.91	6.0×6.0	13.7×13.7	31.4×31.4

3. INFRA-RED COMMUNICATIONS

Optical wireless communications in the near infra-red regime offers much higher data transmission rates than VLC as more powerful and wider modulation bandwidth laser source are being used instead of LEDs. In free space optics it is possible to achieve Gbit/s IR links operating over a few km range [15], but these require higher transmit power within a very narrow field-of-view (FOV). Achieving a wide FOV Gigabit IR communication link for indoor scenario is therefore very challenging as there is a strict constraint on the allowed transmitter power as well as the lack of availability of low cost components at IR wavelengths.

For indoor IR communication links, there are two types of transmission mechanisms: (i) diffuse and (ii) line-of-sight (LOS). Diffuse links generally offer much lower speeds (or data rate in a given room) compared to LOS links. This is mainly due to the multipath induced inter-symbol interference (ISI). However, diffuse links offers a wide FOV and a certain degree of mobility. The concept of a diffuse Gbit/s OW system has been discussed in [16] where parallel low speed transmission have been proposed. A performance analysis of the high speed parallel OW transmission link has been reported in [17]. In [18] an artificial neural network based equalizer with a 'soft' decision decoding scheme has been proposed as an alternative technique to mitigate the multipath induced ISI in indoor OW links, thus increasing the data rate by orders of magnitude. On the other hand the LOS links are the most power and bandwidth efficient for high speed applications since the optical power is highly concentrated and there is no loss or pulse dispersion due to multipath. However, precise alignment and link blocking is a major problem in LOS links, thus limiting its application to a specific environment. In [19, 20] it has been shown that mobility and the coverage area in LOS links can be improved increased by beam broadening.

To increase the FOV of an indoor high-speed IR link, one needs to adopt a cellular communication scheme. In cellular systems the coverage can be increased when multiple narrow FOV links are combined together to form a wider FOV. Figure 3(a) shows a schematic of a typical cellular LOS system, (fabricated as part of the EU Framework 7 OMEGA project [21],) which includes a base station (BS) and a number of user terminals (UT). Both BS and UTs have identical transceivers so that their FOV with matching profiles. Figure 3(b) and 3(c) depict a simulation of the coverage area and received power distribution on the receiving plane for a 7-cell IR link.

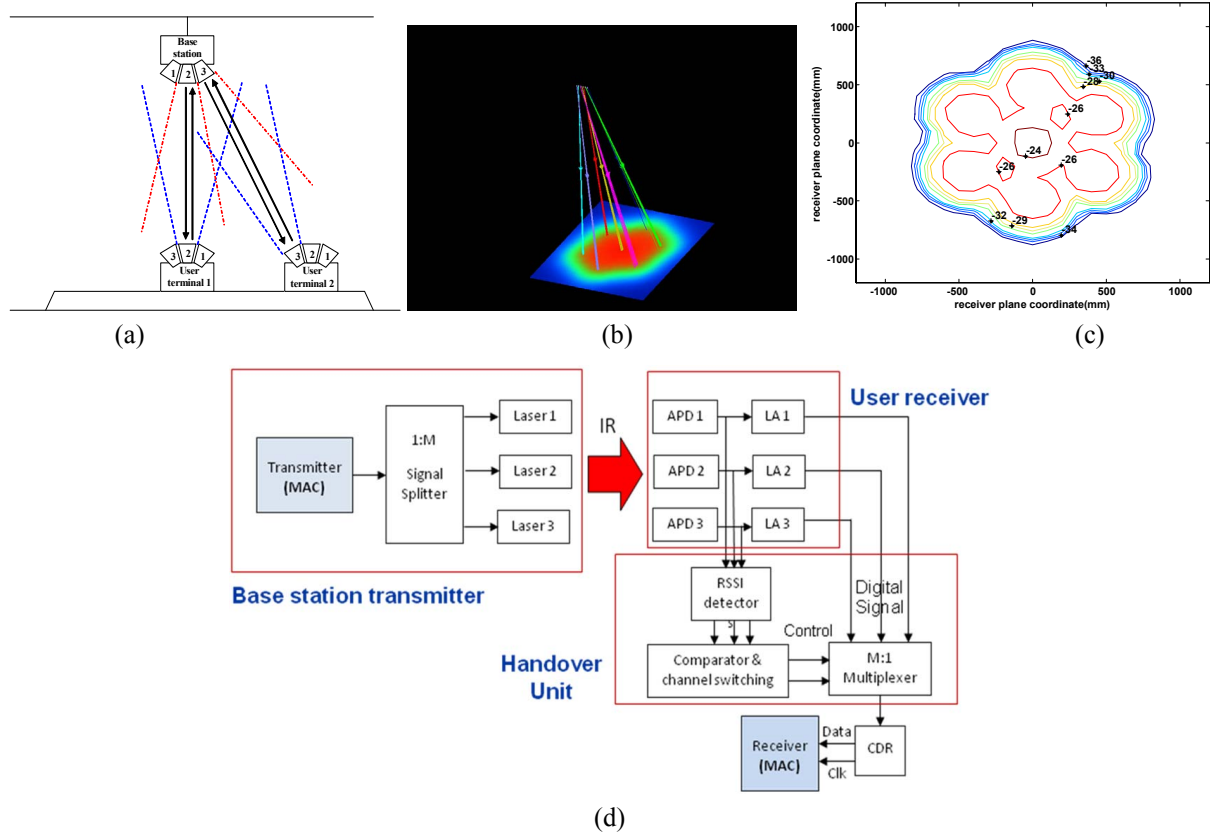


Figure 3: (a) LOS cellular IR communications system; (b) simulated cellular system model; (c) received power distribution in the receiving plane; (d) block diagram of base station and user terminal.

Figure 3(d) illustrates a functional block diagram of the link. At the transmitter side, input data is divided and used to modulate the laser sources. The receiver consists of three receiving modules that collect light from three directions (cells) simultaneously. Received signal strength indicators (RSSI) from all receivers (or cells) are then evaluated to determine which cell is currently available for communications. When the power level of the received signal at a given cell is greater than a pre-defined threshold (at which the target bit error rate (BER) $< 10^{-9}$), the demultiplexer will route the received signal to the clock and data recovery (CDR) module. The data stream is then retimed and together with the recovered clock is forwarded to data layer. In the overlapped region of two cells the RSSI values of two receivers could be greater than the threshold level, therefore the cell with the lower given index number (e.g. Rx1 has lower given index number than Rx2) will be selected. This is achieved using a simple priority encoder integrated digital circuit. Although this approach does not select the receiver with the best signal power level, but it offers a robust handover for this initial demonstration purposes.

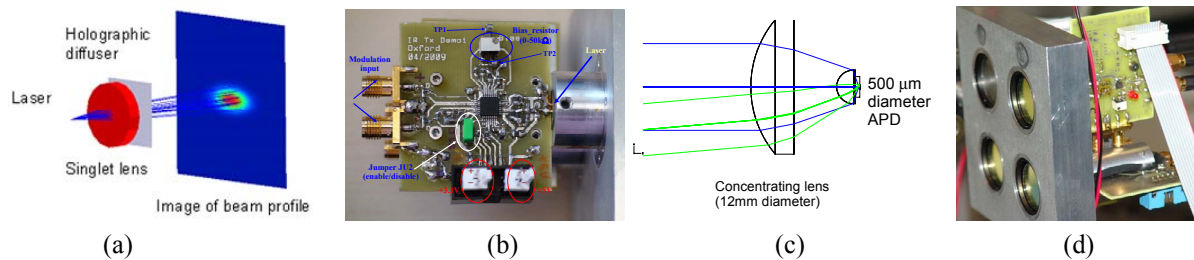


Figure 4: (a) Transmitter's optics design; (b) laser driver; (c) receiver's optics design; (d) optoelectronics circuit.

Figure 4 outlines the design and practical implementation of the Gbit/s optoelectronics subsystems for transmitter and receiver. The system was calibrated and tested [22]. It has been shown that a measured BER of as 10^{-11} has been achieved for 1.25 Gbit/s NRZ-OOK link over a 3 m range and a coverage area of $1.3 \text{ m} \times 0.45 \text{ m}$ with no forward error coding. The transmitter is designed such that it satisfies the laser class I standard.

4. CHALLENGES

4.1 Visible Light Communications

Perhaps the simplest method to alleviate the low modulation bandwidth of a white LED is to filter out the phosphor component using a blue filter, as shown in Table 1. However this incurs a power penalty as energy in other parts of the optical spectrum are blocked (see Figure 1(b)). The data transmission rate can also be increased by employing an equaliser and complex modulation schemes. MIMO systems have the potential to offer higher transmission capacity up to Gbit/s by transmitting data in parallel and continuously updating the channel matrix to separate data at the receiving end. In the scenarios where the channel matrix is not a full rank or ill-conditioned (due to the position symmetry of transmitters/receivers [13]), data from different sources cannot be separated properly, thus resulting in errors. In [14] it is shown that it is possible to improve the channel matrix rank by employing an imaging lens system.

Another challenge for the high-speed VLC is light dimming which affects the link performance. There are two main approaches for dimming: (i) amplitude reduction and (ii) pulse width modulation (PWM). In the first approach increasing the link power budget could help to maintain the link target performance. On the other hand data transmission combined with PWM dimming, is required to operate in burst mode and to coordinate with the duty cycle of dimming pulses. This leads to the reduction of the average data transmission throughput.

4.2 Infra-Red Communications

The main challenge in Gbit/s IR communications is to provide a wide communication coverage. As transmit power is limited by the eye safe regulation, using a number of transceivers in multiple-cell could mitigate the narrow FOV issue, albeit the system is increasingly complex and costly.

Operating at multi-Gbit/s IR communications is challenging due to the low link power budget as the number of photons per bit decreases significantly. Tracking could be employed that may help to reduce receiver FOV and the number of cells. Additionally, fabrication of a high-speed OW receiver is very challenging. At a data rate of 10 Gbit/s a typical photo-detector diameter is less than $100 \mu\text{m}$, thus making receiver fabrication a challenging task.

5. CONCLUSION

Gigabit/s optical wireless systems offer the potential to increase capacity substantially in high speed indoor wireless communications. There are a number of technological and regulatory challenges to be solved. Nevertheless overcoming these issues would make low-cost and high data-rate system feasible. It is feasible that Gbit/s indoor optical wireless links will play a role in providing broad band communication capacity in the future wireless systems.

REFERENCES

- [1] K.-D. Langer and J. Grubor, "Recent developments in optical wireless communications using infrared and visible light" in *Proc. ICTON 2007*, 2007, p. Tu.D3.1.
- [2] J. P. Javaudin, M. Bellec, D. Varoutas, and V. Suraci, "OMEGA ICT project: Towards convergent Gigabit home networks," in *Book OMEGA ICT project: Towards convergent Gigabit home networks*, 2008, pp. 1-5.
- [3] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Transactions on Consumer Electronics*, vol. 50, pp. 100-107, 2004.
- [4] <http://www.vlcc.net/>.
- [5] <http://www.ict-omega.eu/>.
- [6] "IEEE 802.15 WPAN Task Group 7 (TG7) Visible Light Communication," <http://www.ieee802.org/15/pub/TG7.html>.
- [7] "Infrared Data Association," <http://www.irda.org/>.
- [8] H. Le-Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "High-speed visible light communications using multiple-resonant equalization," *IEEE Photonics Technology Letters*, vol. 20, pp. 1243-1245, 2008.
- [9] J. Grubor, K.-D. Langer, S. C. J. Lee, T. Koonen, and J. W. Walewski, "Wireless high-speed data transmission with phosphorescent white-light LEDs," in *Proc. ECOC 2007*, 2007.
- [10] H. Le-Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "100-Mb/s NRZ Visible light communications using a postequalized white LED," *IEEE Photonics Technology Letters*, vol. 21, pp. 1063-1065, 2009.

- [11] J. Vucic, C. Kottke, S. Nerreter, A. Büttner, K.-D. Langer, and J. W. Walewski, "White light wireless transmission at 200+ Mb/s net data rate by use of discrete-multitone modulation," *IEEE Photonics Technology Letters*, vol. 21, pp. 1511-1513, 2009.
- [12] H. Le-Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "80 Mbit/s visible light communications using pre-equalized white LED," in *Proc. ECOC 2008*, 2008, p. P.6.09.
- [13] L. Zeng, D. C. O'Brien, H. Le-Minh, G. E. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, "High data rate multiple input multiple output (MIMO) optical wireless communications using white LED lighting," *IEEE Journal on Selected Areas in Communications*, vol. 27, pp. 1654-1662, 2009.
- [14] D. O'Brien, "Optical multi-input multi-output systems for short-range free-space data transmission," in *Proc. CSNDSP 2010*, 2010.
- [15] G. Nykolak, P. F. Szajowski, G. Tourgee, and H. Presby, "2.5 Gbit/s free space optical link over 4.4 km," *Electronics Letters*, vol. 35, pp. 578-579, 1999.
- [16] F. E. Alsaadi and J. M. H. Elmirghani, "Performance evaluation of 2.5 Gbit/s and 5 Gbit/s Optical wireless systems employing a two dimensional adaptive beam clustering method and imaging diversity detection," *IEEE Journal on Selected Areas in Communications*, vol. 27, pp. 1507-1519, 2009.
- [17] G. Ntogari, T. Kamalakis, and T. Sphicopoulos, "Performance analysis of space time block coding techniques for indoor optical wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 27, pp. 1545-1552, 2009.
- [18] S. Haykin, "Neural networks expand SP's horizons," *IEEE Signal Processing Magazine*, vol. 13, pp. 24-49, 1996.
- [19] A. Hussain, J. J. Soraghan, and T. S. Durrani, "A new adaptive functional-link neural-network-based DFE for overcoming co-channel interference," *IEEE Transactions on Communications*, vol. 45, 1997.
- [20] S. Rajbhandari, Z. Ghassemlooy, and M. Angelova, "Bit error performance of diffuse indoor optical wireless channel pulse position modulation system employing artificial neural networks for channel equalisation," *IET - Optoelectronics*, vol. 3, pp. 169-179, 2009.
- [21] D. C. O'Brien, G. Faulkner, H. Le-Minh, O. Bouchet, M. E. Tabach, M. Wolf, J. W. Walewski, S. Randel, S. Nerreter, M. Franke, K.-D. Langer, J. Grubor, and T. Kamalakis, "Gigabit optical wireless for a home access network," in *Proc. PIMRC 2009*, 2009, pp. 1-5.
- [22] H. Le-Minh, D. O'Brien, and G. Faulkner, "A Gigabit/s indoor optical wireless system for home access networks," in *CSNDSP 2010*, 2010.